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Adaptive stochastic resonance method for impact signal detection based on sliding window

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ABSTRACT

Aiming at solving the existing sharp problems in impact signal detection by using stochastic resonance (SR) in the fault diagnosis of rotating machinery, such as the measurement index selection of SR and the detection of impact signal with different impact amplitudes, the present study proposes an adaptive SR method for impact signal detection based on sliding window by analyzing the SR characteristics of impact signal. This method can not only achieve the optimal selection of system parameters by means of weighted kurtosis index constructed through using kurtosis index and correlation coefficient, but also achieve the detection of weak impact signal through the algorithm of data segmentation based on sliding window, even though the differences between different impact amplitudes are great. The algorithm flow of adaptive SR method is given and effectiveness of the method has been verified by the contrastive results between the proposed method and the traditional SR method of simulation experiments. Finally, the proposed method has been applied to a gearbox fault diagnosis in a hot strip finishing mill in which two local faults located on the pinion are obtained successfully. Therefore, it can be concluded that the proposed method is of great practical value in engineering.

1. Introduction

Vibration analysis is one of the common and effective technologies widely applied in the field of mechanical fault diagnosis [1–4]. As an important carrier of mechanical equipment condition information, vibration signals generated by different mechanical faults tend to vary. Therefore, various signal processing methods based on vibration signals have been widely researched and applied in the extraction of fault features to effectively identify different mechanical faults [5–8]. For example, Wang et al. proposed an effective AR model-based technique for the detection and diagnosis of gear faults [9]. Impact signals are a common form of vibration signal in mechanical engineering, and often contain important information as to the operating condition of mechanical equipment, enabling them to be one of the most important sources of information about mechanical fault features [10–13]. Stochastic resonance (SR), as a nonlinear signal processing method which can be used to extract weak signal features from the vibration signal, has been widely studied in the mechanical fault diagnosis field by right of its unique advantage of using noise to enhance weak signals instead of eliminating noise [14–17].

SR was first introduced by Benzi et al. [18,19] in their study on ancient Earth's weather problems. SR, as a nonlinear physical phenomenon, can not only amplify sine-like signal but also enhance aperiodic signal to some extent [20,21].

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Hu et al. studied the SR phenomenon of aperiodic impulse signal by means of simulation of electric circuit in 1992 [22]. Collins et al. in 1996 [23] studied the aperiodic SR in three additional systems and drew the conclusion that noise can serve to enhance the response of a nonlinear system to a weak input signal no matter whatever it was periodic or aperiodic. In 2007, Leng et al. studied the SR characteristics of a single bistable system and two bistable systems connected in series for periodic and aperiodic signal detection, and found that a cascaded system had higher output signal-to-noise ratio [24]. Although SR can enhance aperiodic signal and its detection capability has already been confirmed, there is very little literature about the performance research and application research of SR for impact signal detection, especially in the field of mechanical fault diagnosis. After the analysis from the research, it is found that two major problems that restrict the application of SR for impact signal detection in the fault diagnosis of rotating machinery are summarized. One is the selection of measurement index. Kurtosis index can be applied to evaluate the resonance effect of SR for impact signal detection and select the optimal system parameters for resonance system by right of its sensitivity to impact component in the vibration signal. However, kurtosis index is not only dependent on the impact amplitude but also related to the number of impact components. The greater the number is, the smaller kurtosis index is, and vice versa. Thus some impact components with small amplitudes might fail to be detected due to the influence of the impact components with large amplitudes when the maximum of kurtosis index is used to evaluate the resonance effect of SR for impact signal detection. Therefore, in view of the influence existing between the number of impact components and kurtosis index, kurtosis index is not good to use as a measurement index of SR for the detection of impact signal with different impact amplitudes, especially when impact amplitudes differ greatly. Correlation coefficient can characterize the similarity of two different signals. The greater the similarity of the two signals is, the greater the absolute value of correlation coefficient is. However, correlation coefficient is susceptible to noise in the weak impact signal detection when it is used as a measurement index to evaluate the resonance effect of SR. Thus, it is necessary to construct a new measurement index to efficiently evaluate the resonance effect of SR for impact signal detection. The other problem concerns efficiently detecting impact signal with different impact amplitudes. The impact signal with different impact amplitudes in this study has two meanings: one is that the amplitudes of impact signal generated by one impact fault in each cycle are different; another one is that the amplitudes of impact signal generated by two or more impact faults are different. The amplitude and number of impact components in the vibration signal still have a great influence on the resonance effect of SR for impact signal detection, even though the influence power can be weakened to some extent by appropriate measurement index. And it is still difficult to ensure that some impact components with small amplitudes can be detected effectively. Therefore, it is necessary to study the SR method for impact signal detection and its application in mechanical fault diagnosis to improve the practical ability of SR in engineering.

In view of the above-mentioned problems which are of deep concern, the present study investigates SR technology for impact signal detection and proposes an adaptive SR method based on sliding window. A weighted kurtosis index is constructed in consideration of the advantages and disadvantages of kurtosis index and correlation coefficient. By means of the maximum of weighted kurtosis index, this method can implement an optimal selection of system parameters. In order to make up the disadvantages of using weighted kurtosis index to evaluate the resonance effect of SR for the detection of impact signal with different impact amplitudes, an algorithm of data segmentation based on sliding window is proposed. The impact signal with different impact amplitudes can be segmented into multiple sub-signals with single impact components by this algorithm to avoid the mutual influence, and achieve the effective detection of SR for impact signal. Simulation experiments and engineering application demonstrate that the proposed method is validated to be effective in detecting the weak impact signal in the fault diagnosis of rotating machinery, even though there are great differences between the impact amplitudes of impact signal.

In the present work, the classical SR theory is introduced in Section 2, and the SR characteristics of impact signals are analyzed in Section 3. Then, in Section 4, the algorithm flow of adaptive SR method based on sliding window is described in detail. And the effectiveness of the proposed method is verified by the simulation experiments and engineering application in Section 5. Finally, conclusions are drawn in Section 6.

2. The fundamental theory of classical SR

SR is a nonlinear physical phenomenon where weak signals are enhanced and the noise is weakened through the interaction of a small parameter signal and noise with a nonlinear system model, whose dynamic behavior can be described by the Brownian motion equation of particles. Therefore, the overdamped SR equation with a nonlinear bistable model can be written as follows:

$$\frac{dx}{dt} = ax - bx^3 + s(t) + n(t) \tag{1}$$

where $x(t)$ denotes the system output, parameters a and b are positive real number, $s(t)$ is a input periodic/aperiodic signal, and $n(t)$ is a Gaussian white noise. The potential function is $U(x) = -(a/2)x^2 + (b/4)x^4$ with two stable points $x_\pm = \pm\sqrt{a/b}$ and one critical stable point $x_0 = 0$. The height of potential barrier is $\Delta U = a^2/4b$.

According to the Brownian motion equation of particles, the system output is actually the Brownian particle trajectory in the potential function $U(x)$. In the absence of the periodic input signal and noise, the position of the Brownian particle is determined by the initial conditions and never changes.